SKAME

SOFTWARE FOR KINEMATIC APPLICATIONS AND MULTIPATH EVALUATION

(ESA/ESTEC Contract No. 16934/02/NL/LvH/bj)

Summary Report

SKAME-GMV-TN-0007

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Issue: 1.0
Date: November, 2004

GMVSA 21007/04

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DOCUMENT STATUS SHEET

Issue	Date	Pages	CHANGE(S)	Approval
1.0	November 2004	37		

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1 INTRODUCTION

1.1 PURPOSE

This document is the Summary Report of the SKAME project.

1.2 SCOPE

This document is a GMV's delivery in the frame of the contract with ESA/*ESTEC "SKAME: Software for Kinematic Applications and Multipath Evaluation*".

1.3 STRUCTURE OF THE DOCUMENT

The document is organised as follows:

- Section 1 is this introductory chapter.
- Section 2 includes the applicable documents and the acronym definition used along the document.
- Section 3 provides a general overview of the project.
- Section 4 explains some aspects related to the Integer Ambiguity Resolution process.
- Section 5 describes the experimental campaign and the Real-World simulator developed during the project.
- Section 6 presents a summary of the results for all the scenarios of the experimental campaign.
- Section 7 analyses in detail two selected scenarios of the test campaign with real data.
- Section 8 offers the conclusions of the project.

2 REFERENCES

2.1 APPLICABLE DOCUMENTS

Reference	Title	Code
[SOW]	Statement of Work. Innovative GPS Navigation Techniques. Software for Kinematic Applications and Multipath Evaluation (SKAME)	TOS-ETT/2002.89/AG Issue 1.0 18 September 2002
[PROPOSAL]	GMV'S Proposal to ESTEC for "Innovative GPS Navigation Techniques: SW for Kinematic Applications and Multipath Evaluation". In Response to the ESTEC SoW Reference TOS-ETT/2002.89/AG	GMVSA 1122/02 November 27th, 2002
[ARADAD]	SKAME: Application Requirement Assessment Document. Algorithm Definition	GMVSA 20266/03 V4/04 November, 2004 Version 4.0
[SRD]	SKAME: Software Requirement Document	GMVSA 20267/03 V4/04 November, 2004 Version 1.0
[TPTP]	SKAME: Demonstration Test Plan and Test Procedures Document	GMVSA 20369/03 V3/04 November, 2004 Version 3.0
[SDD]	SKAME: SW Design Document	GMVSA 20483/03 V3/04 November, 2004 Version 3.0
[SUM]	SKAME: SW Package User's Manual	GMVSA 20207/04 V2/04 November, 2004 Version 2.0
[TRD]	SKAME Test Result Document	GMVSA 20942/04 November, 2004 Version 1.0
[MOPS]	Minimum Operational Performance Standards	RTCA, DO-229A, June 8, 1998

2.2 REFERENCE DOCUMENTS

Reference	Description
[1]	"The Null Space Method for GPS integer ambiguity resolution." M. Martín-Neira, M. Toledo, A. Peláez. Proceedings of DSNS'95, Bergen, Norway, April 24-28, Paper No. 31.
[2]	"Civilian GPS: The benefits of three frequencies", Hatch,R., J.Jung, P.Enge, B.Pervan. (2000).*GPS Solutions*, 3(4)
[3]	"A Comparison of TCAR, CIR and LAMBDA GNSS Ambiguity Resolution", P.Teunissen, P.Joosten, C.Tiberius, ION-GPS September 2002.
[4]	Niell, A. E. "Global mapping functions for the atmosphere delay at radio wavelengths", J. Geophys. Res., 101, pp. 3227-3246, February 1996.
[5]	B.W. Parkinson & J.J. Spilker, Editors, "*GPS: Theory and Applications, Volume I*", Progress in Astronautics and Aeronautics, 1996
[6]	S.Bassiri and G.A.Hajj , *"Higher-Order ionospheric effects on the global positioning system observables and means of modelling them"*, Manuscripta Geodaetica, 18:280-289, 1993

2.3 ACRONYMS

CP	Carrier Phase
AWGN	Additive White Gaussian Noise
DD	Double Differences
DF	Dual-Frequency
FF	Formation Flying
GF	Geometry Free (Method for Integer Ambiguity Resolution).
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
ID	IDentifier
IAR	Integer Ambiguity Resolution
N/A	Not Applicable
NSM	Null Space Method (Method for Integer Ambiguity Resolution).
PC	Personal Computer
PDA	Personal Digital Assistant
PR	Pseudorange
PSD	Power Spectrum Density
RAIM	Receiver Autonomous Integrity Monitoring
RW	Real World
SKAME	Software for Kinematic Applications and Multipath Evaluation
SD	Single-Differences
SF	Single-Frequency
SW	Software
SWL	Super Wide Lane

TBD	To Be Defined
TBW	To Be Written
TF	Triple-Frequency
TCAR	Three-Carrier Ambiguity Resolution
WL	Wide Lane
WP	Work Package
w.r.t.	with respect to

3 GENERAL OVERVIEW

In the frame of a co-funded project with the Navigation section of ESTEC, GMV has developed a PC software prototype (*Navegantis*), which is intended to provide the user with the capability of friendly processing GPS or Galileo observables, in order to compute navigation solutions for a wide range of possibilities:

- Three navigation modes:
  - *Absolute*: navigation position&velocity for one receiver, based on pseudoranges.
  - *Pseudorange (PR) Relative*: relative position&velocity between two receivers, based on pseudoranges. PR-Relative mode will be referred to simply as *Relative* along the documents of the SKAME project.
  - *Carrier-Phase (CP) Relative*: relative position&velocity between two receivers, based on Carrier-Phases (able to provide sub-decimetre accuracy). CP-Relative mode will be referred to as *Kinematic* along the documents of the SKAME project.
- *Post-Processing* (measurements from Rinex files) or *Real Time* (in relative modes, measurements can be transmitted via Radio from *reference* to *user* receiver).
- Multisystem/Multifrequency: prepared for current and future GPS and Galileo (processing of any observable for up to three frequencies).
- Several formats for the navigation solution: *Geocentric*, *Geodetic* and *Topocentric*.

In addition to position and velocity, a number of interesting magnitudes can be computed, stored in files and plotted: DoP values, clock bias&drift, zenith troposphere, ambiguities and residuals.

A number of pre-processing modules are supported by *Navegantis*, which can be activated or inhibited by the user in order to improve the features of the raw measurements:

- Hatch filter for pseudorange smoothing with carrier phases (configurable length).
- Klobuchar model for single-frequency ionospheric correction (recommendable only for absolute navigation).
- Cycle-slip detection and correction, suitable for static or dynamic scenarios (in the dynamic case, Dual-Frequency carrier-phases are required).
- Tropospheric correction based on meteorological Rinex (if available) or standard a-priori models, with Niell mapping functions.
- RAIM to detect/exclude *bad* pseudoranges, based on Chi-squared gaussian tests.

In order to cancel/mitigate some errors, the relative navigation modes (with Pseudorange or Carrier-Phase) are based on double differences of the observables from both receivers, with respect to a pivot satellite. With this approach, hardware bias and clock errors cancel out, while atmospheric (ionosphere and troposphere) and ephemeris errors almost cancel for short baselines (due to their smooth spatial dependence), so that only thermal noise and multipath remain. However, these atmospheric and orbit effects become less and less mitigated for longer and longer distances between receivers, so that they turn out to be the most serious threats to sub-decimetre accuracy in the *Kinematic* mode.

Navegantis runs in any standard PC with Windows operative system and is managed through a friendly Graphical User Interface (GUI), which allows the user to control a large number of configuration parameters as well as plotting the output results (see examples of some configuration screens in Figure 1 to Figure 5).

The project has included an experimental campaign for validating the tool and assessing its performance in several scenarios, by using both real and simulated data. Such simulated data have been provided by a SW simulator in Matlab (also developed within the frame of the project), which can be configured to generate GPS or Galileo measurements (up to three frequencies) in a wide-range of scenarios (Static/Dynamic, Space/Terrestrial, configurable levels of disturbances: Ionospheric, Tropospheric and Orbital errors, as well as thermal noise and multipath).

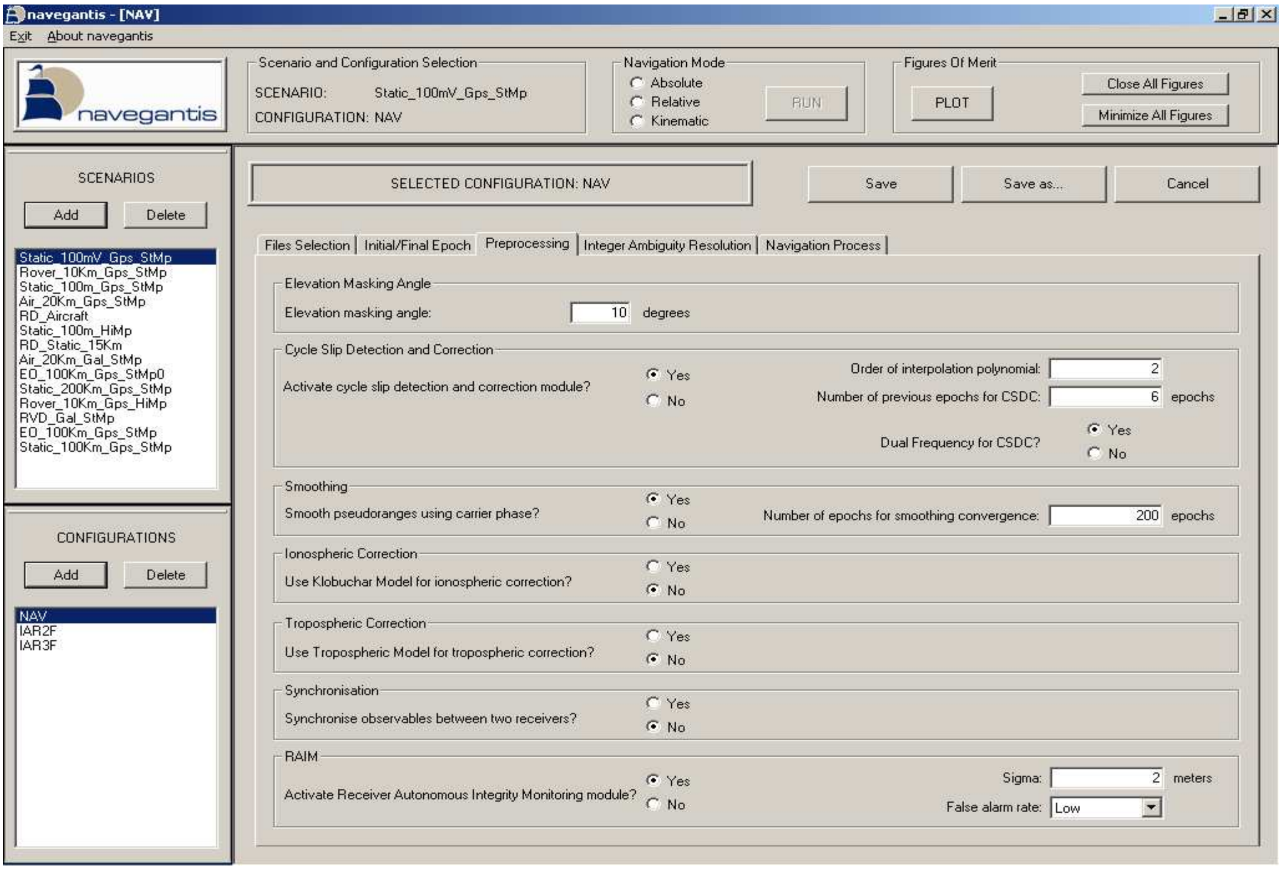

Figure 1.- Navegantis GUI: Screen for configuring pre-processing tasks

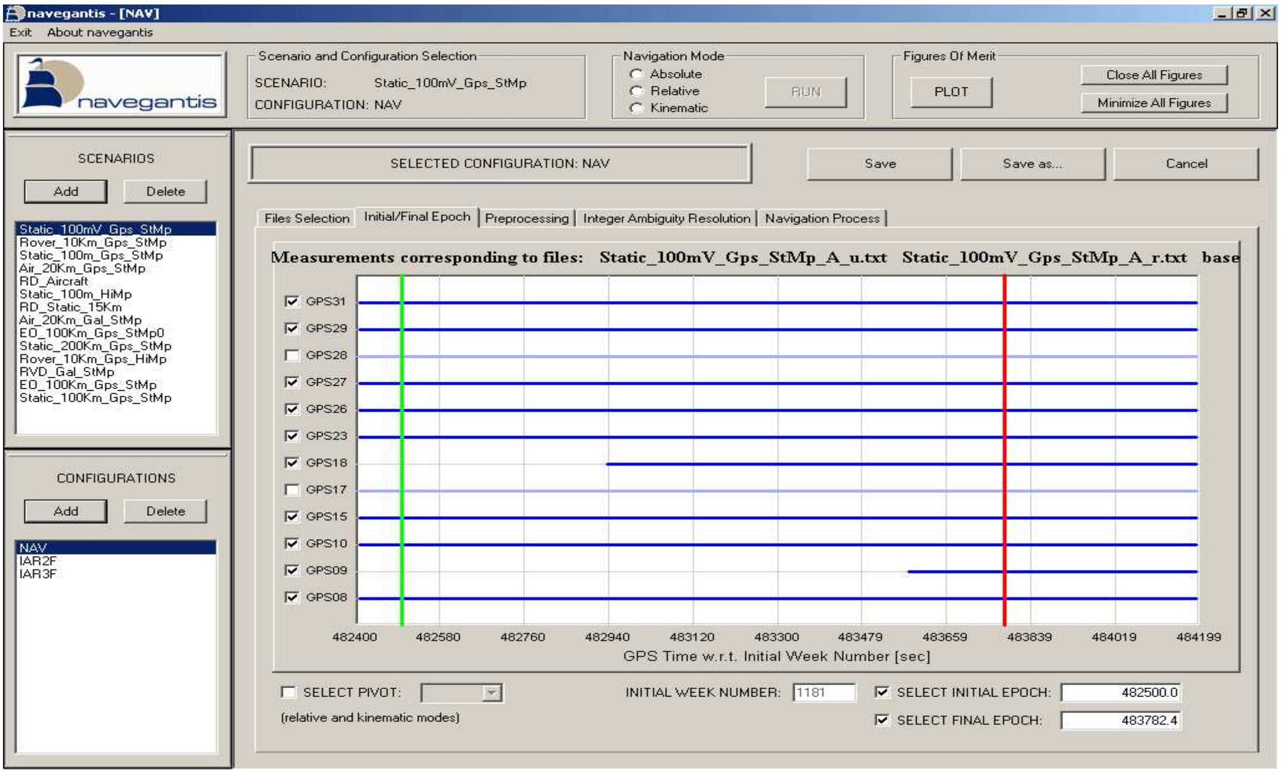

Figure 2.- Navegantis GUI: Screen for satellite and epoch-selection

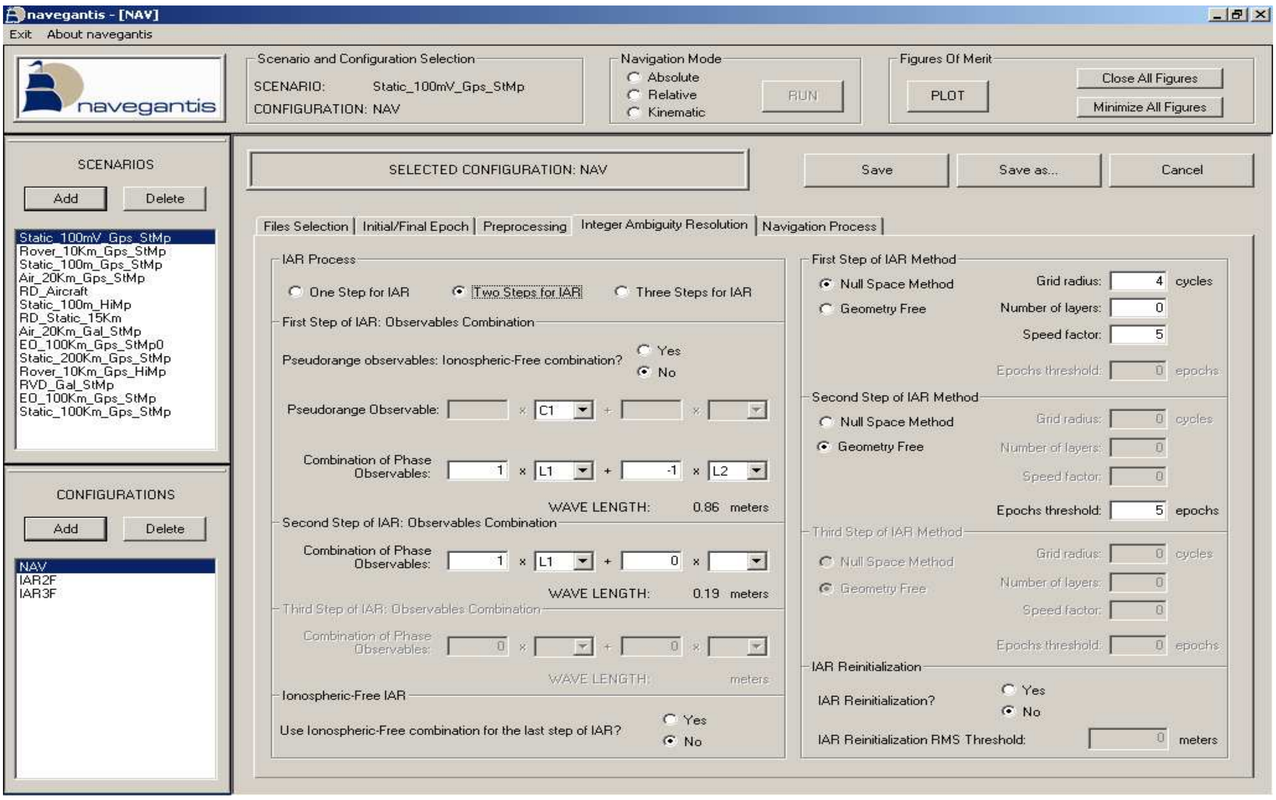

Figure 3.- Navegantis GUI: screen for configuring IAR process

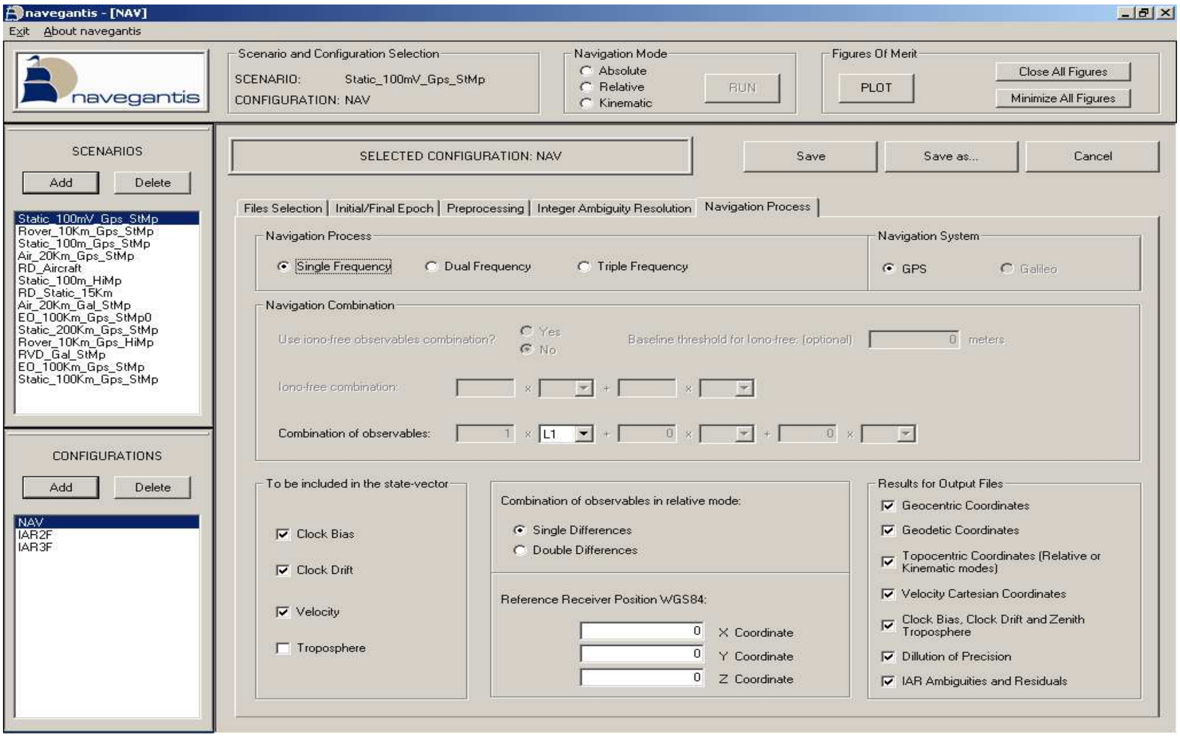

Figure 4.- Navegantis GUI: screen for configuring navigation process.

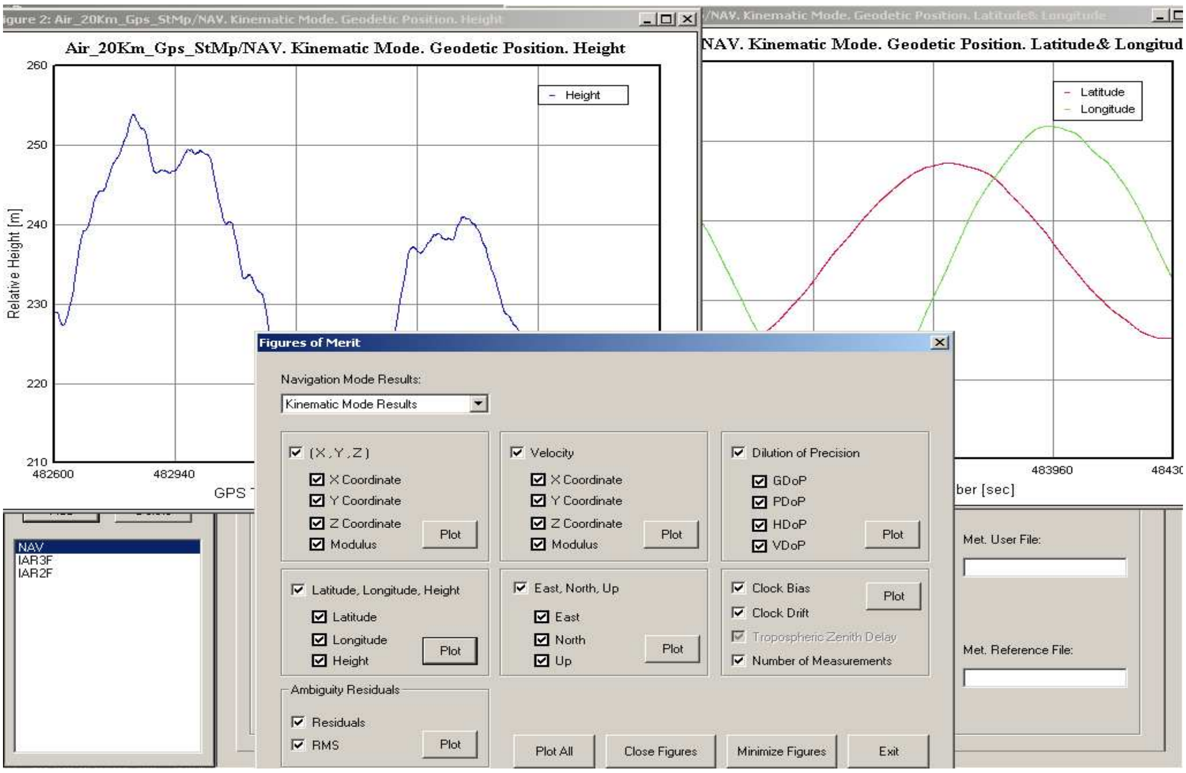

Figure 5.- Navegantis GUI: Plotting capabilities

4 INTEGER AMBIGUITY RESOLUTION FOR KINEMATIC MODE

In order to achieve sub-decimetre accuracy in the solution, navigation in *Kinematic* mode can be based on any of the available carrier-phase observables or any arbitrary combination of them. Prior to being able to use carrier phases, a process for solving the integer ambiguities of the carrier cycles is required. In order to improve this Integer-Ambiguity-Resolution (IAR) process, advantage can be taken of the several frequencies foreseen for Galileo and modernised GPS. In this way, the IAR process in *Navegantis* can be split in as many steps as frequencies are available for the Carrier-Phase observables (1,2, or 3), each step consisting of an arbitrary (configurable) combination (lane) of frequencies. Typically, the frequency combinations for the different steps should be defined in decreasing order of wavelength. The IAR process for the first step makes always use of the pseudoranges, while the other steps are based on the non-ambiguous carrier-phases of the previous step. Table 2 presents some possible Wide-Lane combinations for (future) GPS and Galileo. With current GPS, WideLane L1-L2 can be used (with equivalent wavelength of 0.86m).

		Frequency (MHz)	Wavelength (m)
GPS	L1	1575.42	0.1903
	L2	1227.60	0.2442
	L5	1176.45	0.2548
Galileo	L1	1575.42	0.1903
	E6	1278.75	0.2344
	E5a	1176.45	0.2548

Table 1. Frequency plan for future GPS and Galileo

	Combination	Wavelength (m)
GPS	SuperWideLane L2-L5	5.86
	WideLane L1-L2	0.86
	WideLane L1-L5	0.75
Galileo	SuperWideLane E6-L5a	2.93
	WideLane E6-L1	1.01
	WideLane L1-E5a	0.75

Table 2. Possible Wide-Lane combinations (examples)

In *Navegantis*, the IAR process for each step can be based (configurable) on any of the two following methods:

- *Null-Space Method* (NSM). The NSM [1] is a Geometry-dependent method that tries to exploit the cross-consistency between all the available carrier-phases measurements (for different lines of sight), assuming that, with the true ambiguity vector, all the measurements will be consistent with each other (from the geometric point of view, disregarding the effects of the disturbances). Hence, the corresponding residual will be minimum, while wrong ambiguities will yield larger residuals. The procedure for each step starts by generating a grid of candidates of ambiguity vectors, centred around the best-available baseline solution (computed with pseudoranges or previous-step non-ambiguous carrier phases). Then, the residuals for each ambiguity candidate vector are evaluated and compared against a threshold during consecutive epochs in order to reject them until, eventually, only one remains. This will be considered the ambiguity solution. Time averaging of the residuals is, in general, required in order to mitigate temporary effects of noise and multipath on the residuals, which could yield a wrong ambiguity solution. With the NSM, at least one degree of freedom is required in order to get redundancy in the measurements, so that residuals can be computed. Since the state vector is 3D (only baseline, no clock), a minimum of four DD measurements is required during the IAR process (not during navigation…). This means, in fact, five PRN's, since one of them is used as pivot.

- *Geometry Free (GF)*. In this method, the ambiguities are solved independently for each Line-of-Sight (LoS), based on low-pass filtering of a "geometry free" observable, which is computed by subtracting the noisy non-ambiguous observable from the less-noisy ambiguous carrier-phase, in such a way that the geometric range disappears. Additionally, the differential tropospheric and ephemeris errors (which may not be negligible for medium or long baselines) also cancel out, in such a way that only differential ambiguities, ionosphere and noise+multipath remain in the GF observable. Low-pass filtering over several (probably many) epochs is usually required in order to reduce the noise&multipath level of the non-ambiguous observable below the wavelength of the observable whose ambiguity is being sought, in order to be able to round to the integer solution. Since each LoS is treated independently, no redundancy is required, so that the GF IAR process can be carried out with a minimum of three DD measurements (four PRN's).

Each of these IAR methods are suited for different conditions:

- As long as the remaining tropospheric+orbital disturbances in the pre-processed double differences are not very significant compared to the wavelength, the NSM performs better, since the residual for each candidate is computed with their own carrier phases. Hence, the noise level in the residuals is expected to be much smaller than the wavelength (notice that the pseudorange or wider-lane solutions are used only for initialising the centre of the grid, around which the candidates are defined). On the contrary, the noise of the GF observable is driven by that of the noisier non-ambiguous observable (pseudorange or wider-lane, depending on the step), so that longer filtering may be required for reliable integer rounding.

- When tropospheric+orbital disturbances in the pre-processed double differences are significant compared to the wavelength, performance of the NSM worsens, since the residual of the true candidate can become stabilised in a non-minimum value (low-pass filtering over the time will not mitigate the bias) and a false ambiguity candidate is obtained. Since both troposphere and ephemeris become cancelled in the GF observable, this technique can be more suitable for such conditions (although ionospheric errors not only cannot be compensated, but they get increased in the GF observable).

In order to illustrate the concept of how to choose the IAR method for each step, let us show some examples:

- Scenario1.- Horizontal short baseline (1-5 Km): tropospheric, ionospheric and orbit are negligible. NSM will be used in all the steps (WideLane and L1).
- Scenario 2.- Medium or long baseline (tens or hundred Km). If the tropospheric error can be properly compensated by activating the Niell-model correction, NSM could be used. Otherwise, GF should be probably used, at least in the last L1 step, in order to make the IAR process insensitive to troposphere.

Anyway, this seems to be a some-how controversial issue, since the literature collects “contradictory” preferences about Geometry-dependent and Geometry-free IAR methods, [2],[3].

5 TEST CAMPAIGN AND SW SIMULATOR

In order to test the performance of the tool under different conditions in *Kinematic* mode, a test campaign has been carried out in the frame of the project. The campaign has been organised at a two-fold level, depending on the source of the data:

- *Simulated data from a software Test Bench*, in which the observables are simulated at software level for a number of selected scenarios. In this simulated-data approach, there exists full control on the configuration of the scenarios and, therefore, exhaustive analysis is possible. In this sense, a wide range of test cases have been defined for GPS and Galileo, by sweeping on some *scenario conditions* as well as on some parameters of the Navegantis tool.
- *Real data* (dual frequency) coming from real receivers tracking real GPS satellites.

Navegantis is able to work in three navigation modes: *Absolute* (one-receiver, pseudoranges), *Relative* (two receivers, pseudoranges) and *Kinematic* (two receivers, carrier phases). Out of these three, *Kinematic* mode is the most constraining, since IAR must be performed. In this sense, most of the tests are related to *Kinematic* mode.

For generation of the simulated scenarios, the SKAME project included the development of a small SW simulator in Matlab, able to support Real World generation with the following features:

- GPS and Galileo, with measurements in up to three-frequencies.
- Configurable dynamics of reference and user receivers: *On-ground* and *Space*.
- Atmospheric effects:
  - Ionosphere: Klobuchar model is used in order to represent the spatial variability of the Total Electron Contents and the slant ionospheric error. High-order effects (up to fourth order) are considered for the frequency dependence of the ionospheric errors [6], so that the simulator can be realistically used to check mitigation of ionosphere based on Dual-Frequency combinations.
  - Troposphere: The MOPS WAAS/EGNOS model [MOPS] is used to simulate the zenith tropospheric delay of each receiver (as a function of its specific position), with mapping functions for translation into slant error (for each LoS). Of course, *Navegantis* should not be configured for tropospheric correction based on Niell model with such simulated files, since both models (simulation and processing) are quite similar and results would be unreliably good.
- Orbit errors are simulated as 3D Gauss-Markov processes (Radial, Along and Across), of configurable sigmas.
- Receiver effects: thermal noise (white noise, elevation-dependent configurable sigmas) and multipath (Gauss-Markov processes, with configurable characteristic-times and elevation-dependent sigmas).
- Cycle slip generation for the Carrier-Phase measurements, with configurable probability of occurrence.

5.1 SCENARIOS WITH SIMULATED DATA

5.1.1 Definition Criteria for the simulated scenarios

The test cases in the simulated–data context have been classified in two main sets, depending on the environment involved: *Space* and *On-ground*. The main differences between these two environments (which must be accounted for when the observables are generated) are assumed to be related to:

- ***Atmospheric perturbations*** on the observables: in space environment, there will be no tropospheric error; the ionospheric shift will be quite smaller than in the on-ground scenarios.
- ***Absolute dynamics*** of the receivers w.r.t. the GPS constellation, which will be much higher in Space than on ground. [Notice that we are referring here to *absolute* dynamics, not relative between both receivers!].

In each simulated environment, the tests are defined by considering the following ***driving factors***:

- *Baseline length* (order of magnitude of the distance between reference and user receivers). This magnitude impacts in terms of the level of spatial decorrelation between some of the error components (orbital and ionospheric errors, as well as troposphere in the on-ground scenarios) and, consequently, error mitigation capabilities based on differential processing will be limited. The range of variation of the baseline includes three possibilities: short (<1Km), medium (10-20 Km) and long (≈100 Km).
- *Multipath*. Two possible levels have been considered: *standard* (most of the scenarios) and *high* (two scenarios). Multipath has been simulated as Gauss-Markov processes with elevation-dependent sigmas. In high-multipath cases, the Gauss-Markov processes will be increased in a factor "2" w.r.t the standard-multipath cases.
- *Level of dynamics*. This must be interpreted in a different way for Terrestrial and for Space environment:
  - In on-ground cases, the reference receiver is assumed static, while the user receiver can have three levels of dynamics: static, medium (Rover, ≈10m/s) or high (small airplane, ≈100m/s).
  - In space, both receivers (reference and user) are orbiting and will have a very high absolute dynamics (w.r.t. the constellation of navigation satellites), but the relative between both receivers dynamics will be small (Formation Flying, Rendezvous&Docking…).

The following issues have been taken into account in order to generate the simulated scenarios:

- *Available frequencies*.- Three-Frequency observables have been always generated in the observation files. The availability of two or more frequencies can be exploited in two ways: mitigation of the ionospheric error and/or helping the Integer-Ambiguity-Resolution process for the Kinematic mode. The simulated files will always include the three possible frequencies, to check how the joint use of several frequencies improves the performance of the IAR process.
- *Ionosphere*.- The ionospheric error in the simulated files have been simulated based on the Klobuchar model for each receiver. In space scenarios at Low Orbit (some 400 Km height), the

ionospheric error is expected to be smaller than on-ground. On the other hand, the Klobuchar model is defined for on-ground receivers. With this in mind, the approach followed to simulate the ionospheric error in space environment has been to directly use the Klobuchar model, by using the instantaneous longitude and latitude of the space receivers, assuming zero height (instead of the actual 400 Km), and applying a weighting factor of ½.

- *Forced* cycle *slips*: all the files include randomly-generated cycle slips, in order to show that they are automatically detected and corrected by the cycle-slip detection and correction algorithm.

5.1.2 Simulated scenarios

The test campaign with simulated data has been organised as presented in Table 3 (for on-ground scenarios) and Table 4 (for scenarios in space).

SCENARIO ID	TYPICAL APPLICATION	DRIVING FACTORS			NAV system
		Baseline	Multipath	Dynamics	
S_G_Static_100mH_Gps_StMp	Topography/ Geodesy	Very short (100m Horizontal)	Standard	Static	GPS
S_G_Static_100mH_Gps_HiMp	Topography/ Geodesy	Very short (100m Horizontal)	High	Static	GPS
S_G_Static_100mV_Gps_StMp	Atmospheric sounding	Very short (100m Vertical)	Standard	Static	GPS
S_G_Static_100Km_Gps_StMp	Topography/ Geodesy	Long (100Km, Same geodetic height)	Standard	Static	GPS
S_G_Rover_10Km_Gps_StMp	Rover guidance	Medium (10Km Horizontal)	Standard	Medium	GPS
S_G_Rover_10Km_Gps_HiMp		Medium (10Km Horizontal)	High	Medium	GPS
S_G_Air_20Km_Gps_StMp	Aircraft guidance for low-flying applications (seaplanes)	Medium (20Km, 200m height)	Standard	Medium	GPS
S_G_Air_20Km_Gps_StMp		Medium (20Km, 200m height)	Standard	Medium	Galileo

Table 3.- Scenarios for the ***ON-GROUND*** *environment, with* ***simulated-data***

SCENARIO ID	TYPICAL APPLICATION	DRIVING FACTORS			NAV system
		Baseline	Multipath	Dynamics	
S_S_RVD_Gal_StMp	Rendezvous & Docking	Very short (<250m Horizontal)	Standard	Absolute: Very high Relative: Low	Galileo
S_S_EO_100Km_Gps_StMp	Stereoscopic Earth Observation	Long (100Km, same orbit)	Standard	Absolute: Very high Relative: Static	GPS

Table 4.- Scenarios for the ***SPACE*** *environment, with* ***simulated-data***

The thermal noise has been simulated as white noise with elevation-dependent sigma and the multipath as Gauss-Markov processes with characteristic time of 100 seconds and elevation-dependent sigma: see

Figure 6 for the standard deviations of the thermal noise and the multipath errors (standard and high multipath), for pseudorange and carrier phase measurements, as configured for the simulated scenarios in the test campaign.

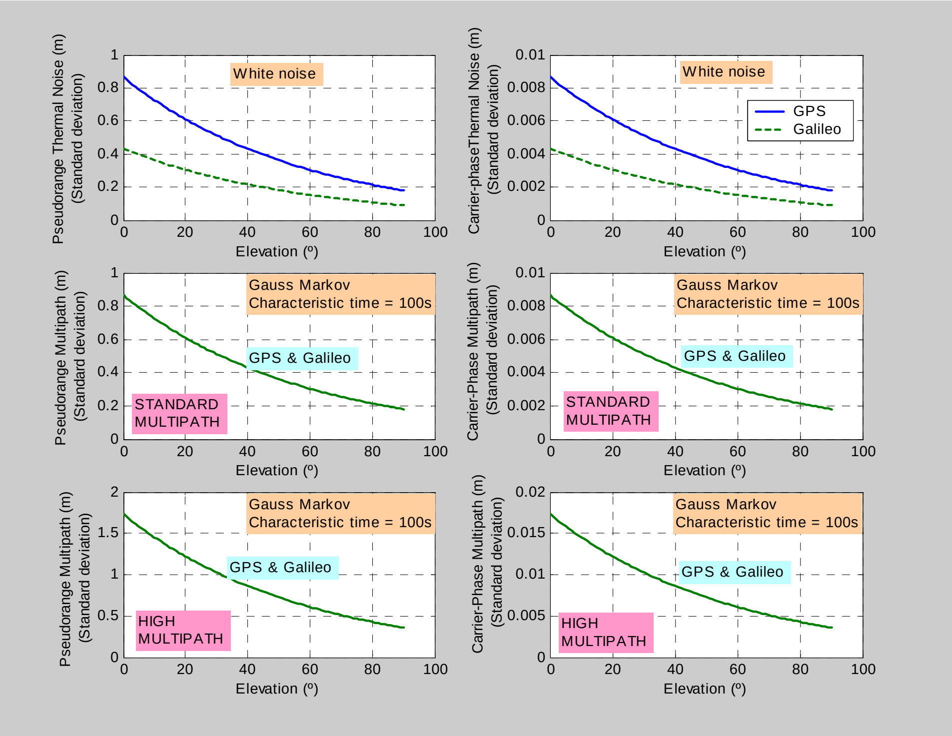

Figure 6.- Standard deviations of the noise and multipath errors (PR and CP) used for the simulated scenarios, as a function of the elevation.

5.2 SCENARIOS WITH REAL-DATA

With real data, only on-ground scenarios have been considered, since no Space data are available. Two issues have been taken into account in order to define the scenarios:

- *Baseline length* (see Section 5.1.1 for more details). The range of variations includes four possibilities: very short (≈100 m), short (<1 Km), medium (≈15 Km) and long (≈100 Km).
- *Dynamics*. In this case, there are two possibilities: static and medium (in the case of the rover scenario).

The multipath level has to be left "unforced" in the sense that the observables will have the multipath error corresponding to the environment itself, without imposing any "artificial" control. Dual Frequency has been assumed for the measurements.

Table 5 presents the four real-data scenarios analysed during the experimental campaign with *Navegantis*.

Scenario ID	Typical Application	Driving factors	
		Baseline	Dynamics
RD_Static_100m	Topography/Geodesy	Very short (100m Horizontal)	Static
RD_Static_15Km	Topography/Geodesy	Medium (15 Km) Relative geodetic height ≈300m	Static
RD_Rover_1Km (*RT)	Rover guidance	Short (<1Km)	Medium
RD_Static_100Km	Topography/Geodesy	Long (100 Km) Relative geodetic height ≈0m	Static

Table 5.- Scenarios and configurations for the ***ON-GROUND*** *environment, with* ***real-data***

6 SUMMARY OF RESULTS

Performance of Navegantis in all the scenarios presented in the previous chapter has been analysed and carefully described in [TRD]. The current chapter is a summary of those results.

The level of thermal noise and multipath used for the simulated test cases can be found in Figure 6.

6.1 SIMULATED, ON-GROUND, GPS

Note: With simulated files, the Niell **tropospheric correction** has **not** been activated in *Navegantis*, because the model used for simulation and for compensation would be very similar and the results would be perhaps too good. On the contrary, the tropospheric error has been left in the measurements in order to somehow simulate what would happen in those cases for which the Niell model is not able to remove the tropospheric errors, due for example to unmodellable local conditions in each receiver (local wet delay…). [Tropospheric correction based on the Niell model is checked in the real-data tests.]

6.1.1 Static, very-short baselines (100m)

Three different scenarios have been tested with very-short baselines and GPS observables:

- Horizontal baseline, standard multipath.
- Horizontal baseline, high multipath (factor 2 w.r.t. to standard multipath).
- Vertical baseline, standard multipath.

Summary of results:

- In general, IAR based on NSM performs properly:
  - With Dual Frequency, correct IAR convergence can be achieved for the standard multipath case within 10-20 seconds, while convergence is slower in the high multipath scenario (>3 minutes).
  - The use of three frequencies helps very much, reducing the IAR convergence time to 1-3 seconds in the standard multipath case (typically 1s, i.e. instantaneous IAR), and 10-20 seconds with high multipath.
- Navigation errors are very small in the horizontal baseline case (3D RMS: ~1cm with standard multipath and ~2cm with high multipath), while for vertical baseline, the vertical error is biased around 13 cm (due to the tropospheric error).
- Conclusion: Multipath level has deeper impact on slowing the IAR convergence than on navigation accuracy, while, at this level, tropospheric error seems to show the opposite effect.

6.1.2 Dynamic, medium baseline (Rover, low-flying aircraft)

Several scenarios have been tested in dynamic conditions and medium baseline:

- Rover (medium dynamics, ~10m/s), at 10 Km from the reference station, with standard and high multipath in the GPS observables. Despite the distance of 10Km, remaining tropospheric errors are quite small in the double differences (<2-3 cm), since both receivers have similar geodetic heights.
- Low-flying aircraft, with higher dynamics (~100m/s), at 20 Km from the reference station and 200 m height, with standard-multipath GPS and Galileo observables. DD tropospheric error can reach 10-40 cm for low elevation satellites (< 20º). Ionosphere is in the order of 1-2 cm.
- It must be reminded that tropospheric correction is **not** activated in *Navegantis* when processing these simulated files, because the simulation and the compensation of errors would be too similar. Therefore, these results should be interpreted as a conservative case, representative of what would happen when the Niell model is not able to properly mitigate tropospheric errors, due for example to unmodellable local conditions.

Summary of results:

- Rover, Standard Multipath:
  - NSM IAR performs properly, with convergence times in the range of a few tens of seconds when dual-frequency is employed. The use of three frequencies reduced the convergence time to 1-3 seconds (typically 1s, i.e. instantaneous IAR).
  - Navigation errors are in the order of 1 cm for the horizontal component and 3 cm in vertical coordinate.
- Rover, High Multipath (factor 2 in all the measurements, w.r.t. standard multipath):
  - Correct IAR becomes slower, with convergence times around 3 minutes with dual-frequency, and some 30 seconds when three frequencies are used.
  - Navigation errors are only slightly larger than in the standard multipath case, since most of the errors are related to troposphere, and the contribution of higher multipath is marginal.
- Aircraft, Standard multipath, GPS or Galileo:
  - IAR convergence becomes slower in the DF case, due to the disturbing effects of the significant tropospheric biases (5-6 minutes).
  - Navigation solution become biased due to the troposphere, with vertical error about 10-30 cm.

6.1.3 Static, very long baseline (100Km), GPS

One scenario has been tried with two GPS receivers placed at 100 Km from each other, at the same geodetic height, with standard multipath configuration. In such conditions, the atmospheric and orbital errors become quite decorrelated in both receivers, with remaining DD tropospheric error of up to 40 or

60 cm for very-low elevation satellites, while DD ionospheric error is in the order of a few centimetres (up to 8 cm). [It must be reminded that tropospheric correction is **not** activated in *Navegantis* when processing these simulated files, because the simulation and the compensation of errors would be too similar. Therefore, these results should be interpreted as a conservative case, representative of what would happen when the Niell model is not able to properly mitigate tropospheric errors, due for example to unmodellable local conditions].

Summary of results:

In these conditions, results show that navigation must be based on the WideLane combination (L1-L2), since the ambiguities of the L1 carrier phases cannot be reliably computed (an error of one L1 cycle remain for some of the satellites). This is due to the significant ionospheric errors remaining in the double differences, which become amplified in the geometry-free observable (the one tried for trying to solve the L1 ambiguities, in order to cancel the very disturbing troposphere).

Being constrained to the use of the WideLane instead of L1 has two main implications:

- Navigation cannot be performed in ionospheric-free mode, since the L1 and L2 ambiguities are not known.
- The noise of the WideLane observable is larger than for L1 (due to the longer wavelength and the combination of noises from two different measurements).

According to the presented results, the navigation solution is biased some 20-30 cm in both vertical and horizontal coordinates.

[See §6.3.4 for assessment of long-baseline performance with real-data, in which the tropospheric error has been properly mitigated by the Niell model correction.]

6.2 SIMULATED, SPACE

6.2.1 Stereoscopic Earth Observation, Very long baseline (100 Km), GPS

In this scenario, two receivers have been simulated onboard two low-orbit satellites in a common orbit (height of 600 Km) and two different mean anomalies, so that the distance between them is always 100 Km. In this case on space, troposphere is not present at all, and ionosphere is quite reduced (it has been conservatively assumed that the ionospheric effect is in the order of half the one on-ground). Specifically, the remaining DD ionospheric errors in the simulation have turn out to be below 2 cm for all the satellites. Orbital error is in the same order.

Summary of results:

- With dual frequency, IAR convergence took properly place typically in less than one minute, while with three frequencies, the convergence time became reduced to 3-5 seconds.
- Navigation accuracy is in the order of 5 cm (RMS).

6.2.2 Rendezvous and Docking, Short baseline (< 500m), GPS or Galileo

This scenario has been simulated as two receivers onboard two low-orbit spacecraft, with one of them approaching the other (starting from 250 m). In this case, only noise and multipath errors remain in the double differences.

Summary of results:

- With dual frequency, IAR took place properly typically in 30 seconds, while with three frequencies the convergence time was reduced to 1-3 seconds.
- Navigation accuracy is in the order of 1 cm.

6.3 REAL-DATA, ON-GROUND

6.3.1 Static, very-short baseline (100m)

For this scenario, two Dual Frequency receivers (intended for professional applications, i.e. of high quality) were placed at a distance of about 100m from each other, in the horizontal plane.

Summary of results:

- Performance of IAR with the Null-Space Method was excellent, since the typical convergence time was less than 10 seconds, even with single frequency.
- The navigation error cannot be computed, because the true positions are not exactly known. But the analysis of the residuals show that accuracy must be in the order of 1 cm.

6.3.2 Real Time, Dynamic (car), short baseline (< 1 Km)

For this experiment, the same two receivers were used, one of them static (reference) and another on-board a car. The reference receiver was transmitting its observables via short-wave radio to the user receiver, in order to carry out CP navigation in real time. The car was in dynamic status, within a maximum distance of 1 Km from the reference receiver (this distance constraint was due to the limited power of the radio transmitter).

Summary of results (see §7.1 for details):

- IAR took place properly within 72 seconds with dual frequency (post-processing of the results have shown out that the IAR algorithm was conservatively configured, since proper convergence could have been achieved in only a few seconds).
- Based on analysis of the residuals and DoP, the navigation accuracy has been estimated in 1-2 cm.

6.3.3 Static, medium baseline (15 Km)

This scenario has been based on Rinex files downloaded from a geodetic service, corresponding to two stations with known positions, at 15 Km from each other and a relative height of 315 m. With such conditions, tropospheric error is expected to be the dominant one in the raw measurements (mainly due to the difference of heights).

Summary of results:

- IAR convergence can be properly achieved in about half minute using dual frequency. During the IAR process, the tropospheric error has been corrected at pre-processing based on the a-priori Niell model (without meteorological data).
- Navigation solution has been computed in four different modes, depending on the CP measurement used (L1 or L1/L2 IonosphericFree combination) and the tropospheric approach (correcting or not correcting the tropospheric error in the raw measurements, based on the a-priori *Niell* model, with no meteorological data):
  - When troposphere is not compensated, the solution is biased, with vertical error (the dominant one) of 20-30 cm. With Ionospheric Free combination, the bias is only slightly reduced, but the solution is a little noisier (due to the noise amplification of the ionospheric-free combination).
  - Correcting the troposphere in the raw measurements (by using the Niell model, without meteorological data) helps very much reduce the vertical bias below the centimeter level. The 3D position error is biased in the order of 3 cm.

6.3.4 Static, very-long baseline (100 Km)

This case is similar to the previous one (downloaded Rinex files), but corresponding to much more distant stations (100 Km). In this case, DD troposphere is expected to be very important, as well as, at a second order, DD ionosphere.

Summary of results:

- In the corresponding simulated case (see 6.1.3), the WideLane ambiguities were correctly solved, but the L1 ambiguities failed (the tropospheric correction was not activated). In this real data case, IAR convergence can be achieved for both WL and L1 because, during the IAR process, the tropospheric error has been corrected at pre-processing based on the a-priori Niell model (without meteorological data). In addition, for the second (and last step) of IAR, the NSM has been applied in iono-free mode.
- IAR convergence can be properly achieved in less than one minute with dual frequency. Nevertheless, in such conditions, almost half of the trials fail, since the IAR process is quite sensitive to the specific errors. In this sense, it has been found out that slowing down the IAR process (several minutes) contributes to increase the probability of proper estimation of the ambiguities.

- Navigation solution has been computed in two different modes, depending on the CP measurement used (L1 or L1/L2 IonosphericFree combination). The tropospheric error is corrected in the raw measurements, based on the a-priori Niell model, with no meteorological data:
    - When the L1 is used (no ionospheric free) the solution becomes biased with an RMS in the order of 15 cm.
    - With Ionospheric Free combination, the solution becomes improved, with 3D position error biased in the order of 5cm.

7 DETAILED ANALYSIS OF TWO SCENARIOS WITH REAL DATA

The previous chapter has collected a summary of Navegantis performance for all the scenarios analysed during the test campaign. The current chapter presents (as an example) a detailed analysis of two of them, based on real data:

- RD_Rover_1Km (*RT): Real Time, Dynamic (Car), Short baseline (<1Km)
- RD_Static_15Km: Post-Processing, Static, Medium baseline (15Km)

For full detailed about the performance in all the other scenarios, the reader is kindly referred to [TRD].

7.1 RD_ROVER_1KM (*RT): REAL TIME, DYNAMIC, SHORT BASELINE (<1KM)

A dynamic experiment was carried out with *Navegantis* and Real Data in Real Time, with the following set-up (Figure 7):

- A Dual-Frequency *Novatel* receiver (OEM4-G2-L1L2) placed at a static location, which will behave as *reference* station, broadcasting (via short-wave radio) its own GPS observables (C1, P2, L1 and L2) by means of a short-wave transmitter.
- A Dual-Frequency *Novatel* receiver (OEM4-G2-RT2) onboard a car (*user*), provided with a short-wave radio to receive the *reference* GPS observables.

The GPS observables coming from both receivers (*Reference* via Radio, and *User*) are real-time downloaded onto a PC card, also on-board the car. This card hosted *Navegantis* and was controllable through a standard PDA. Additionally, both sets of observables (*user* and *reference*) were recorded for post-processing purposes. *Navegantis* was configured to compute relative position and velocity. Tropospheric, ionospheric and orbital errors were assumed negligible in this short-distance experiment, so that navigation was performed with L1. The IAR process was configured to be based on two consecutive steps (WL+L1), with Null-Space Method in both steps.

The car started at some 650 m from the *reference* station and continued moving during 10 minutes within a maximum distance of approximately 1 Km (this short-distance constraint was related to the limited power of the available radio-system). The experiment was carried out in a mild urban environment, with low houses and relatively-wide streets, so that GPS availability was in general good, typically 7 or 8 PRNs, although sometimes it was lower, with a minimum of 4 PRNs during some epochs (see Figure 8).

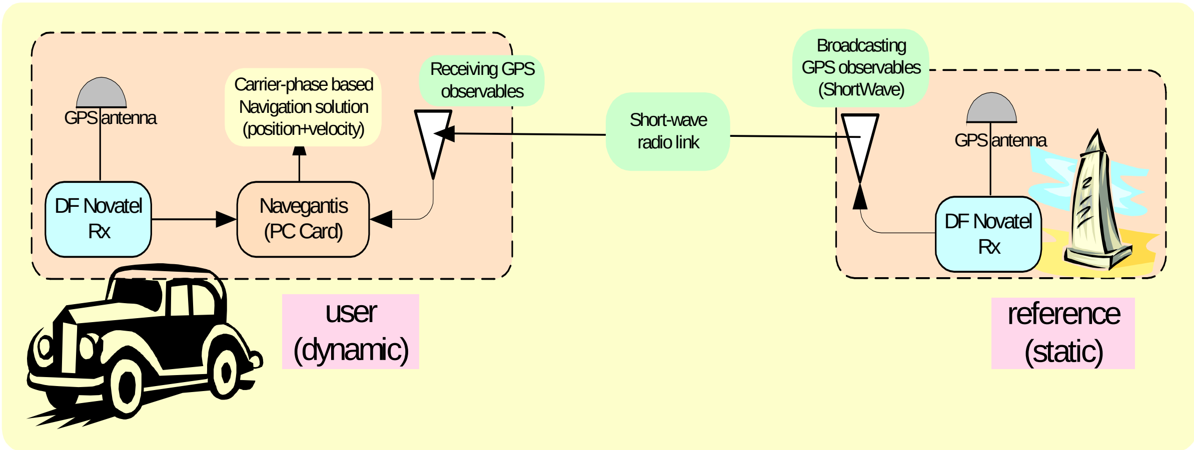

Figure 7.- Schematic description of the Real-Time dynamic experiment

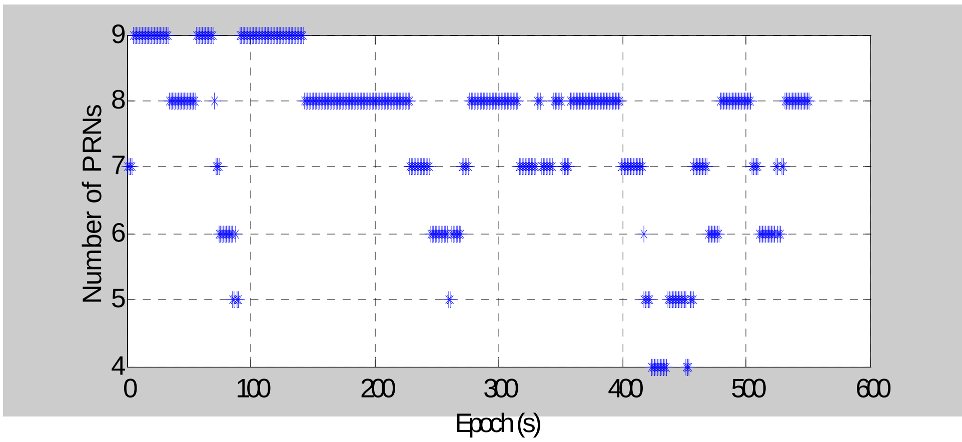

Figure 8.- PRN availability (pivot included), for the dynamic real-time experiment

Results are summarised as follows:

- IAR convergence (based on two consecutive steps: WideLane + L1) took place properly after 72 seconds. It must be clarified that, in order to guarantee proper convergence, the IAR process was conservatively configured in *Navegantis*, on the price of slowing down the process and increasing the convergence time. Post-processing of the data has shown out that convergence could have been in fact achieved within a few seconds. Assessment of the correctness of the ambiguities is based on analysing the evolution of residuals (see Figure 10 *Top*), which remain very low during the whole interval. If ambiguities had been wrongly estimated, the residuals would have presented a clear growing pattern over the time.

- Many PRN's were lost and regained during the experiment, due to temporary occultation in this dynamic environment. Every time, the ambiguities were properly recomputed with the NSM, based on the other already-known unambiguous carrier phases.

- Position errors cannot be computed, since the true positions are unknown (dynamic). Anyway, having in mind that the bias-like errors are fully cancelled in this experiment (troposphere, ionosphere and orbit), an estimation of the accuracy has been elaborated for each epoch as the product between the instantaneous RMS of the residuals and the corresponding DoP value. This is not a fully-rigorous method, but it should provide a clear indication of the expected accuracy. Results are presented in Figure 10 *Bottom*, with a mean value of 2, 1.7 and 1.2 cm for 3D, Vertical and Horizontal estimated accuracy, respectively.

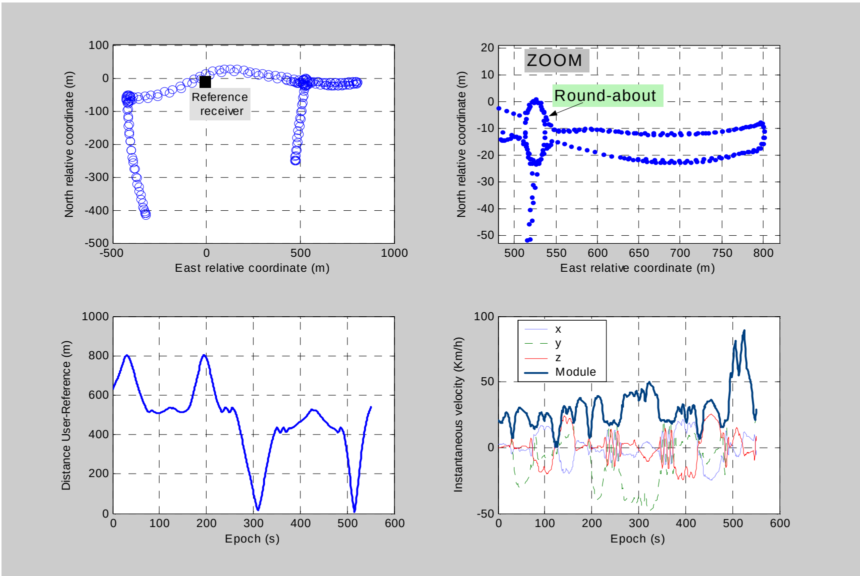

Figure 9.-Top*: Horizontal trajectory (full,* Left*, and zoom,* Right*) of the car during the experiment.* Left bottom: *Evolution of the distance between user (car) and reference antenna.* Right bottom: *Evolution of the velocity (computed by* Navegantis *with carrier phases).*

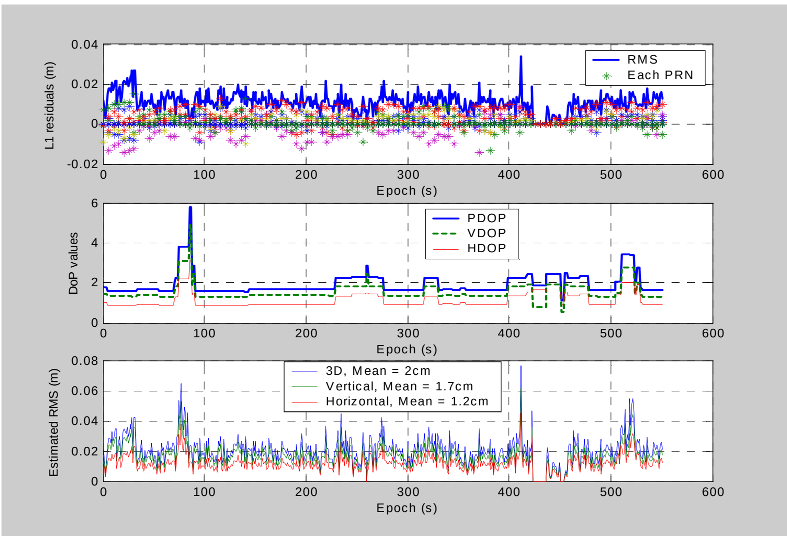

Figure 10 -Top: *Evolution of residuals for the different PRNs and its instantaneous RMS.* Middle: *Evolution of DoP values. Temporary larger DoP's are associated with losses of PRNs.* Bottom: *Estimation of the position accuracy, based on DoP and RMS of the residuals.*

7.2 RD_STATIC_15KM: POST-PROCESSING, STATIC, MEDIUM BASELINE (15KM)

For this scenario, two RINEX files has been downloaded from the Instituto Cartográfico de Cataluña, corresponding to two topographic stations with known position. The stations are identified as GARR and PLAN, both of them located in Catalonia (North-East of Spain, see true coordinates in Table 6). For defining the scenario, GARR has been considered as *reference* and PLAN as *user* (see true baseline coordinates in Table 7). The tested observation files correspond to Week Number 1270 and week seconds between 14400 and 17999.

ID	WGS84			Geodetic		
	X (m)	Y (m)	Z (m)	Lon (º)	Lat(º)	Height (m)
Garr	4796983,846	160308,761	4187340,016	1,91403571993	41,29293755448	634,558
Plan	4787329,060	166085,6500	4197602,490	1,98695172943	41,41852473310	319,998

Table 6.- Coordinates of each station for TC_RD_Static_15Km

WGS84			Topocentric		
X (m)	Y (m)	Z (m)	N (m)	E(m)	Height (m)
-9654,7862	5776,888	10262.474	-13946,6197	-6108,165	296,358

Table 7.- Baseline coordinates for TC_RD_Static_15Km

In this scenario, the baseline is around 15 Km and the difference of heights is almost 300 m. This data determine the level of tropospheric and ionospheric errors in the double differences, although they cannot be known a-priori, since we are dealing with real data. The a-priori tropospheric correction based on the Niell model has been tried in this real-data scenario, so that the remaining tropospheric errors in the pre-processed double differences are expected to be small (although not negligible).

The IAR process has been carried out with Dual Frequency, and the Null Space Method has been employed for both IAR steps (WideLane and L1). Convergence of IAR has properly taken place typically in some 30 seconds.

In this real-data scenario, the true ambiguities cannot be known a-priori and, therefore, comparison with estimated ambiguities is not possible. The decision about the proper convergence of the IAR process has been based on inspection of the residuals. Figure 11 presents the evolution of the RMS of the residuals in two different conditions:

- In the red solid line, the residuals grow up significantly over the time, which means that the ambiguity solution is wrong.
- For the blue dotted line, the RMS of the residuals remain more or less steady, constrained to small values. This is an indication that the IAR has converged to the true ambiguity solution.

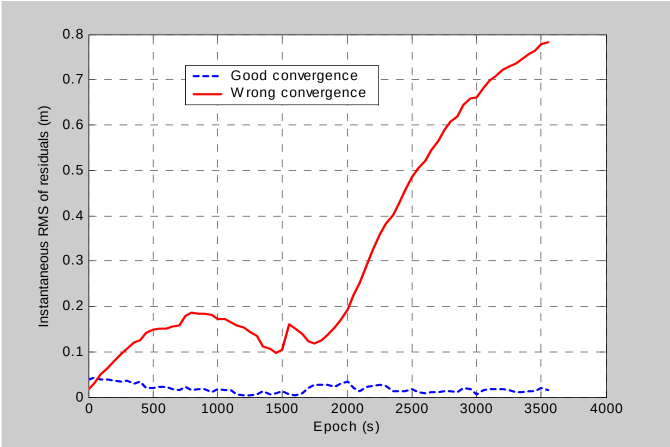

Figure 11.- Evolution of the RMS of the residual for the RD_Static_15Km scenario: when IAR has converged properly (blue dotted) or not (red solid).

Navigation performance has been analysed by processing the scenario in four different modes:

- ***L1***: in this case, nothing has been done regarding ionospheric or tropospheric error (solution based on L1 carrier phases without tropospheric correction).
- ***IonoFree***: Navigation processing based on Dual Frequency ionospheric-free combination for the CP observables (after IAR), without tropospheric correction.
- ***TropoCorr-L1***: A-priori tropospheric correction (in pre-processing) based on the Niell model (no meteorological data); navigation based on L1 CP's.
- ***TropoCorr-IonoFree***: A-priori tropospheric correction (in pre-processing) based on the Niell model (with no meteorological data); navigation based on DF Ionospheric Free CP's.

Figure 12 presents the DoP values for the whole interval of processing (1 hour), as well as the number of PRNs (included pivot).

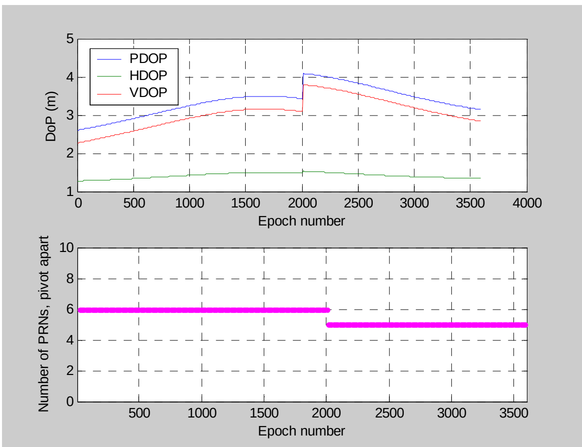

Figure 12.-RD_Static_15Km: DoP values and number of total PRN's (pivot included), for the RD_Static_15Km scenario.

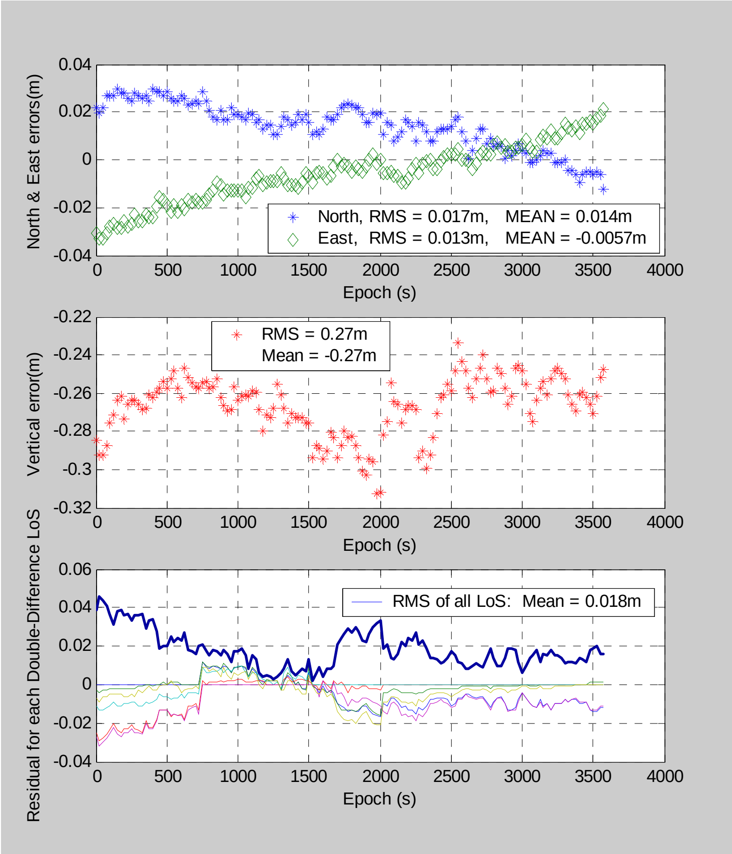

Figure 13.- Navigation errors (North, East & Vertical) and residuals for RD_Static_15Km (L1, No Tropo Free)

In the *NAV-L1* mode (see Figure 13):

- Horizontal errors are in the order of few centimeters: RMS is between 1 and 2 cm for both components (North and East).
- The vertical error is clearly biased to a value of 27cm, with deviations of less than 3 cm from that bias during the whole processing.
- The residuals are small (less than 5 cm in worst case). The small level of the residuals show out that the estimated ambiguities are correct (otherwise, the residuals would undoubtly grow up over the time).

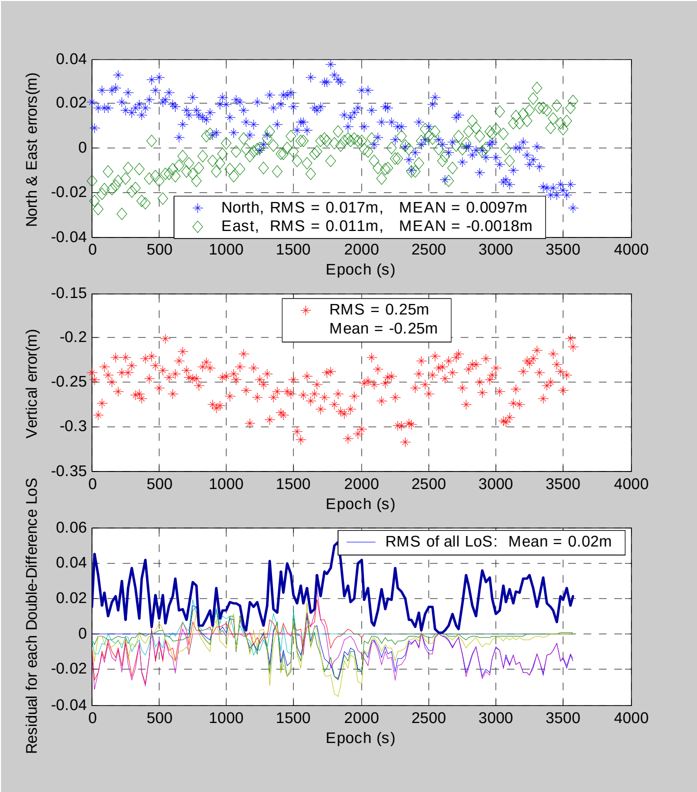

Figure 14.- Navigation errors (North, East & Vertical) and residuals for RD_Static_15Km (Iono Free, No Tropo Free)

In the *ionospheric free processing* (see Figure 14):

- Horizontal errors are in the same order as the *basic processing* (RMS between 1 and 2 cm).
- The vertical error is slightly improved, with RMS of 25 cm (instead of the 27 cm of the basic processing), but the error is less periodic: long-term oscillations are not so clear, and the error evolution is more “white-like” (this is due to the fact that “bias” contribution of the ionosphere is replaced by the less-biased and noisier iono-free combination).
- The residuals are in the same order as in the basic processing (less than 5 cm in worst case), but they are more stationary over the time.

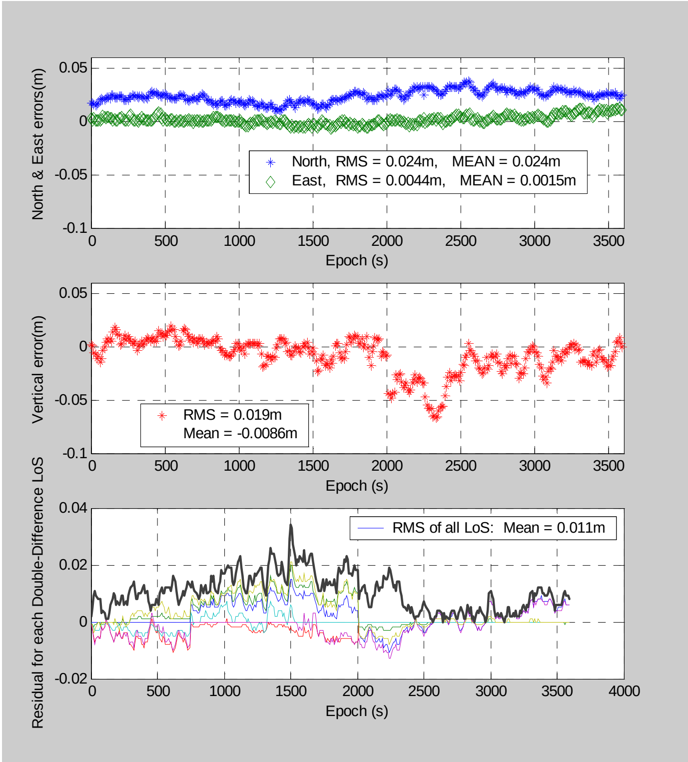

Figure 15.- Navigation errors (North, East & Vertical)and residuals for RD_Static_15Km (L1, Niell tropo correction)

In the *TropoCorr-L1* mode (see Figure 15), the results are much better:

- Horizontal errors are in the same order as for the two previous modes (centimetric level).
- The vertical error becomes very much reduced compared to the previous modes, with unbiased behaviour (mean error in less than 1 cm) and RMS less than 2 cm. This means that the tropospheric correction based on the Niell model is working properly, even in this scenario without meteorological data.
- The residuals are in the order of 1cm, smaller than in the previous cases, since the errors of the navigation solution are smaller and, therefore, all the measurements are more cross-consistent w.r.t. the computed navigation solution.

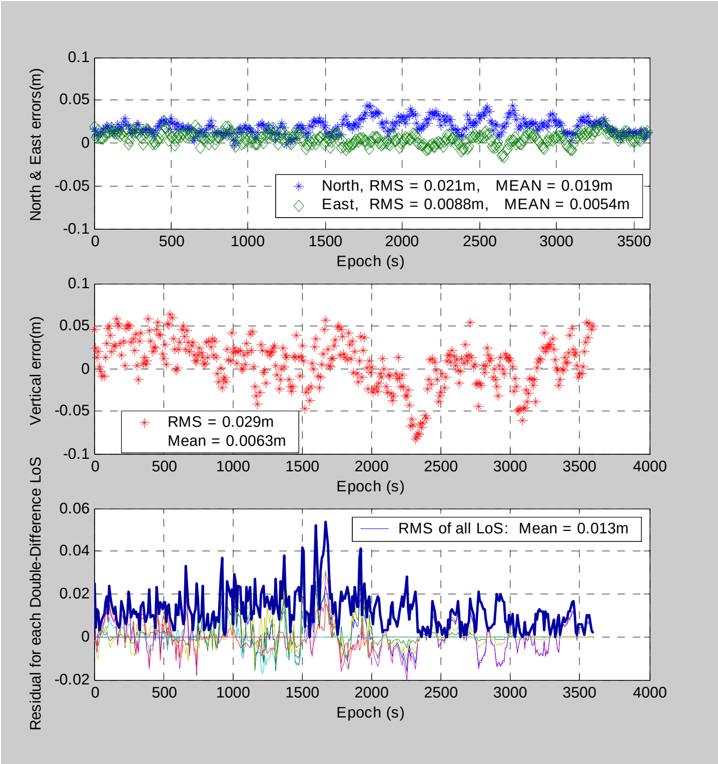

Figure 16.- Navigation errors (North, East & Vertical)and residuals for RD_Static_15Km (Iono Free, Niell Tropo Correction)

In the *TropoCorr-IonoFree mode* (see Figure 16):

- Horizontal errors are in the same order as in the other modes.
- The vertical error is even less biased than in the previous mode (6.3 mm against 8.6mm), which suggests that the remaining ionospheric error in the double differences is being properly compensated. However,the RMS is slightly larger (2.9 cm) because the solution is noisier, due to the noise amplification experienced by the ionospheric free combination of the carrier phases.
- The residuals are small, but slightly noisier due to the ionospheric free combination.

8 CONCLUSIONS

A prototyping SW tool (*Navegantis*) has been developed by GMV in the frame of a co-funded project for the Navigation section of ESTEC. The tool is intended for processing GPS or Galileo observables (up to three frequencies) in several modes: *Absolute* (pseudorange-based absolute), *Relative* (pseudorange-based relative) and *Kinematic* (carrier-phase based relative).

Navegantis runs in a standard PC and is controlled and fully-configurable through a very-friendly GUI, which includes plotting capabilities for all the magnitudes of interest. *Navegantis* implements a number of configurable pre-processing modules (smoothing, RAIM, Ionospheric & Tropospheric models, cycle-slip detection and correction) intended to improving the raw observables.

For the *Kinematic* mode, an Integer Ambiguity Resolution (IAR) process is required prior to being able to use the carrier phase measurements and achieve the sub-decimetre accuracy. For the IAR process, advantage can be taken of the multiple frequencies in the navigation signals. In this way, the IAR process in *Navegantis* can be split in as many steps as frequencies are available for the Carrier-Phase observables (1 or 2 for current GPS, up to 3 for future GPS and Galileo), each step consisting of an arbitrary (configurable) combination (lane) of frequencies (typically, the frequency combinations for the different steps should be defined in decreasing order of wavelength). The IAR process for the first step makes always use of the pseudoranges, while the other steps are based on the non-ambiguous carrier-phases of the previous step. Each IAR step in *Navegantis* can be carried out based on the Null-Space Method or Geometry Free techniques.

In order to test the performance of *Navegantis* under different conditions in *Kinematic* mode (the driving one), a test campaign has been carried out, based on both real and simulated data. For data simulation, a Matlab Real-World generator developed during the project has been used (for Gps or Galileo, three-frequency measurements, two different multipath levels, Terrestrial and Space environment).

The test campaign has shown out the following performance of *Navegantis*:

- For short baselines, IAR performance is excellent, with proper convergence within a few seconds (even with single frequency).
- For medium baselines (~15Km) with real data, proper and fast ambiguity resolution can be acomplished with dual frequency measurements, as long as the tropospheric error can be reliably compensated by the Niell model (as was the case in the described scenario, even without meteorological data).
- For long baselines (100Km), with real data, ambiguity resolution is possible sometimes in around one minute when the troposphere is compensated by the Niell model, but convergence needs to be slowed down in order to guarantee the proper resolution of the ambiguities.
- For short baselines (when tropospheric/ionospheric errors become fully cancelled in the double differences), the accuracy of the navigation solution is in the centimetric order (driven mainly by the noise of the measurements).

- For medium terrestrial baselines (15Km between reference and user receiver), accuracy of the navigation solution can be in the order of 3 cm, when the tropospheric error is properly compensated by the Niell model.
- For long terrestrial baselines (100Km), accuracy of the navigation solution can be in the order of 5-10 cm, when the tropospheric error is properly compensated by the Niell model and dual frequency iono-free combination is used.
- IAR performance with three frequencies (tested with simulated data) seems to yield good results, with often instantaneous IAR (in one single epoch), although it can take sometimes 2 or 3 epochs to converge properly.